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SHC 2015, International Conference on Solar Heating and Cooling for Buildings and Industry

## Parametric analysis of concrete solar collectors

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### Abstract

Concrete solar collectors offer a type of solar collector with structural, aesthetic and economic advantages over current popular technologies. This study examines the influential parameters of concrete solar collectors. In addition to the external conditions, the performance of a concrete solar collector is influenced by the thermal properties of the concrete matrix, piping network and fluid. Geometric and fluid flow parameters also influence the performance of the concrete solar collector. A literature review of concrete solar collectors is conducted in order to define the benchmark parameters from which individual parameters are then compared. The numerical model consists of a 1D pipe flow network coupled with the heat transfer in a 3D concrete domain. This paper is concerned with the physical parameters that define the concrete solar collector, thus a constant surface temperature is used as the exposed surface boundary condition with all other surfaces being insulated. Results show that, of the parameters investigated, the pipe spacing,  $p_s$ , concrete conductivity,  $k_c$ , and the pipe embedment depth,  $d_{emb}$ , are among those parameters which have greatest effect on the collector's performance. The optimum balance between these parameters is presented with respect to the thermal performance and discussed with reference to practical development issues.

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**Keywords:** Concrete solar collector, Façade integration, Simulation

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### 1. Background and study outline

Solar thermal energy is a clean renewable source of energy that can reduce the amount of fossil fuels associated with energy consumption in buildings. In order to expand the solar thermal market, cheaper alternatives that can be integrated into the building's envelope are required. The rationale for façade located solar thermal collectors has been outlined [1] in which hotels, apartments and hospitals have been highlighted as the major consumers of Domestic Hot Water (DHW), thus requiring the full use of the buildings envelope in order to provide for the hot water demands. Precast concrete cladding constitutes a significant proportion of residential, commercial and public building facades worldwide. A high proportion of these buildings were built during 1950s, 60s and 70s which now

require renovation. Concrete Solar Collectors (CSCs) offer a unique solution for the integration of solar thermal technology into precast concrete facades, where pipes can be disguised. As the name suggests, they are a type of solar collector which use a thick layer of concrete as the absorber in place of thin metal sheets. The heat transfer network is embedded within the concrete layer. The lower thermal conductivity of concrete is compensated for by better storage characteristics and benefits of their lower panel cost and architectural integration potential. The aim of this study is to undertake a parametric analysis of CSCs by way of numerical simulation.

### 1.1. Concrete solar collectors

The majority of CSCs have been conceived for roof attached installations [2]–[9], as well as horizontal roof integrated installations [10], [11]. Horizontal wall and facade integrated CSCs have also been investigated; both theoretically [12] and experimentally [13]. The CSCs assessed in the literature varied in terms of both geometry and material properties. Performance enhancements can be achieved through the addition of glazing, insulation and coatings. Glass or plastic covers and insulation can be included, which improves the thermal performance by reducing heat loss [6]–[8], however, a casing system would be required which reduces the CSCs suitability for facade integration. Increasing the absorptance at the face of the collector through the addition of dark coatings can increase the amount of solar radiation captured by the CSC. Unfinished concrete has a solar absorptance,  $\alpha$ , of approximately 0.65, which can be improved to 0.96 by adding a painted finish [8]. The optical properties can be further enhanced by applying a spectrally selective coating to the concrete face which have high absorptance in the solar spectrum and low emittance in the thermal spectrum [6], thus, reducing radiative heat loss.

The effects that a number of individual parameters have on the performance of separate collectors have been assessed experimentally; however a benchmark collector has not been established in order to compare these influences with each other. Positive influences on the CSCs performance have been observed for a reduction in the pipe embedment depth [10], a reduction in the pipe spacing [2] an increase in the pipe's external diameter [12] and an increase in the conductivity of the pipes [4] and concrete absorber [9]. This paper aims at identifying which parameters have the greatest influence on the performance of the CSC within practical limits.

## 2. Methodology

The CSC is simulated using a numerical model with steady state boundary conditions. Steady state conditions are used in this study as a first step in the optimization of the concrete solar collector. This identifies the effect the physical parameters have on the heat transfer from the surface of the CSC to the working fluid. Conservation of energy equations account for the one dimensional fluid flow through the pipe network which is coupled with the three dimensional heat transfer in the concrete domain. Parameters are varied within a realistic range of values and their influence on the performance of the collector is assessed in terms of the temperature difference ( $^{\circ}\text{C}$ ) between the inlet and the outlet ( $T_{in} - T_{out}$ ).

The collector considered in this study is a square  $0.81\text{m}^2$  unglazed CSC with embedded piping as displayed in Fig. 1. A surface temperature of  $40^{\circ}\text{C}$  is used as the boundary condition to simulate a maximum surface temperature received by the CSC under clear sky summer conditions. The inlet temperature and initial temperatures concrete and fluid temperatures are set to both  $10^{\circ}\text{C}$ .

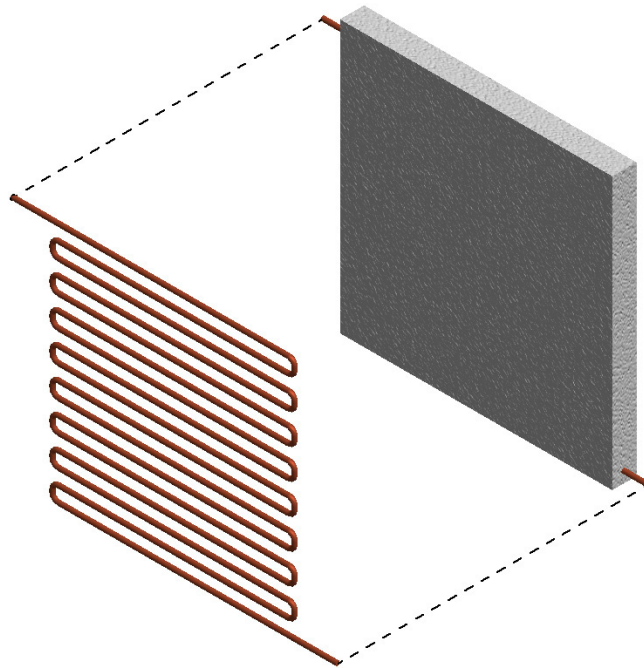


Fig. 1. Scaled schematic of a concrete solar collector displaying embedded pipe.

The performance of CSCs in the literature have been compared in terms of different criteria, including maximum temperature difference between inlet and outlet [10], maximum outlet fluid temperature [8], yearly/daily energy output [12], daily efficiency [7] and payback period [11]. Since this study assesses the performance under steady state conditions the performance of the CSC is compared using the temperature difference between the inlet and outlet ( $T_{out} - T_{in}$ ). The literature on concrete solar collectors is reviewed and used as a guideline for defining the benchmark parameters of the CSC within practical limits. A description of the origin of the benchmark values is provided in Table 1.

Table 1. Benchmark parameters and boundary conditions for CSC model

Parameter	Value	Selection
<b><math>k_c</math> (Concrete conductivity) [W/mK]</b>	<b>2</b>	<b>ISO 10456 [14]</b>
<b><math>k_p</math> (Pipe conductivity) [W/mK]</b>	<b>380</b>	<b>ISO 10456 [14]</b>
<b><math>d_i</math> (Pipe internal diameter) [m]</b>	<b>0.015</b>	<b>Practical value for pipes (literature average 0.017m)</b>
<b><math>d_{emb}</math> (Pipe embedment depth) [m]</b>	<b>0.025</b>	<b>Typical embedment for reinforced concrete (literature average 0.032m)</b>
<b><math>d_s</math> (Pipe Spacing) [m]</b>	<b>0.05</b>	<b>Maximize heat exchange area (literature average 0.088m)</b>
<b><math>\dot{m}</math> (Mass flow rate) [kg/s]</b>	<b>0.01</b>	<b>Lower value from literature to maximize temperature of fluid</b>
Pipe layout	Serpentine	Allows for uniform flow
$\delta$ (Panel thickness) [m]	0.8	Typical thickness of single skin concrete façade elements (literature average 0.07m)
$c_c$ (Concrete heat capacity) [J/kgK]	1000	ISO 10456 [14]
A (Panel area) [m <sup>2</sup> ]	0.81	Matches rig dimensions for future experimental work

The variables used in this study are highlighted in bold in the table above and their effects are individually assessed and then compared in the subsequent sections.

### 3. Results

The results are provided in this section with sub-sections used for each variable parameter.

#### 3.1. Concrete conductivity

The effect the concrete conductivity has on the temperature difference is displayed in Fig. 2. The results show a positive increase in performance with increased concrete conductivity. The concrete conductivity ranges from 0.72 W/mK [10] to 4W/mK [8] in the literature for a CSC.

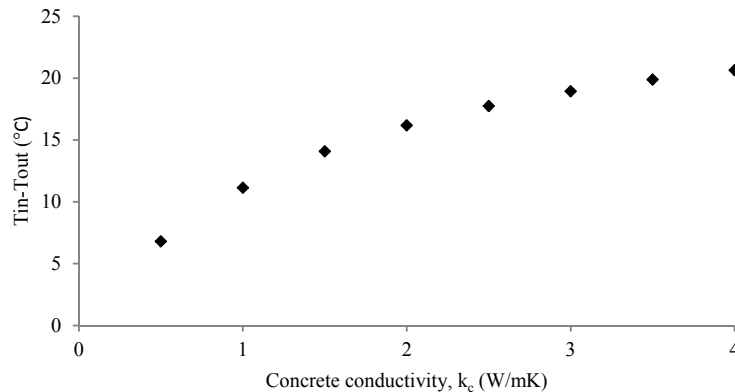


Fig. 2. The performance of a CSC with varying concrete conductivities ( $k_c$ )

The greatest increase in performance is shown at lower conductivities with the temperature difference increasing by 9.4°C from 0.5 to 2 W/mK while the temperature difference increase from 2.5 to 4 W/mK is 2.9°C. Thus, as the conductivity increases the performance returns are diminished. The concrete conductivity may be increased by increasing the density or through the inclusion of conductive materials; however, the increase in conductivity should not be such that the cost of the collector is significantly affected. Further research is required in order to optimize the concrete mixture.

#### 3.2. Pipe conductivity

In addition to increasing the conductivity of the concrete domain the conductivity of the pipe material,  $k_p$ , is also considered. The thickness of the pipe (0.002m) is significantly smaller than that of the concrete absorber (0.08m) thus the effect is less than that of the concrete as shown in Fig. 3. Pipe conductivity is not generally provided in the literature, instead the material used was stated and the associated conductivity can be taken from standards [14].

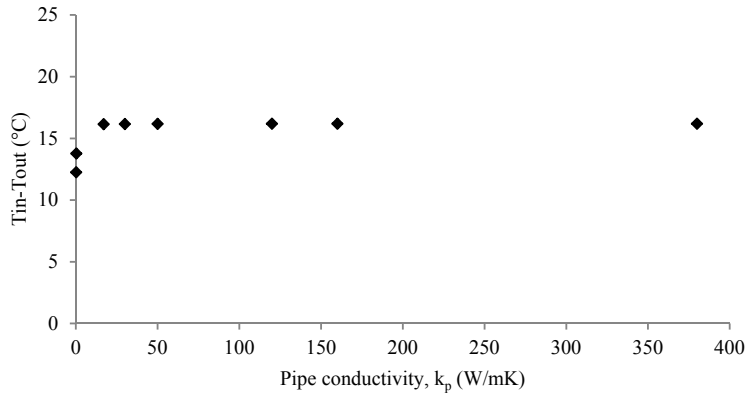


Fig. 3. The performance of a CSC with varying pipe conductivities ( $k_p$ )

Both plastic ( $<1$  W/mK) and metallic pipes ( $>17$  W/mK) have been used in CSCs. An increase in the temperature difference of between  $2.5$  and  $4^\circ\text{C}$  is observed when changing from a plastic to a metallic pipe, depending on the plastic used (e.g.  $k_p = 0.17$  W/mK for PVC pipes). However, no difference greater than  $0.1^\circ\text{C}$  is observed as the conductivity is increased from  $17$  W/mK (stainless steel) to  $380$  W/mK (copper). This can be attributed to the low thickness of the pipes compared with the thickness of the concrete absorber and the fact that the benchmark concrete conductivity is  $2$  W/mK.

### 3.3. Pipe diameter

The influence of the pipe diameter has been assessed but a negligible effect on the temperature difference ( $<1.2^\circ\text{C}$ ) has been observed within the ranges found in the literature ( $0.01$ - $0.0254$ m). This is contrary to results in other literature [12]. However, in that case the pipe was located in the centre of a double exposed wall, therefore increasing the diameter in such case would have a similar effect to reducing the embedment depth, which was shown to have a significant effect.

### 3.4. Pipe embedment depth

Increasing the pipe embedment depth has a negative effect on the temperature difference, however in order for the pipes to be hidden from view they need to be embedded. The closer the pipes are to the surface the greater the increase in the temperature difference (Fig. 4). Thus the pipe plane should be located as close to the surface as possible. One parameter limiting this is the maximum aggregate size used in the concrete. The pipes should be embedded at a depth greater than that of the maximum aggregate size in the concrete mixture as is done with reinforced concrete.

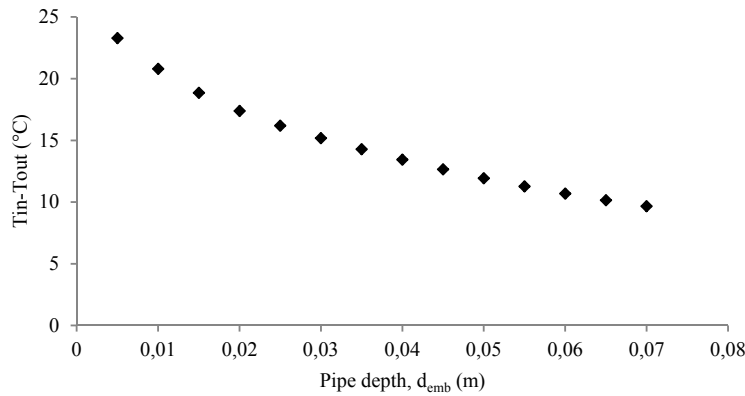


Fig. 4. The performance of a CSC with varying pipe embedment depth ( $d_{emb}$ )

Pipe embedment depth in the literature ranges from being exposed [13] to a 0.1m embedment [15]. Exposing the pipes may be suitable for certain applications but would hinder the aesthetics of the facade if used for facade integration. For the given collector a reduction in the temperature difference of 11°C was found by changing the embedment depth from 0.01m to 0.07m.

### 3.5. Pipe spacing

Closer pipe spacing increases the surface area of the heat exchanger. As expected, increasing the heat exchange area increases the temperature difference. Fig. 5 displays the effect of increasing the pipe spacing. Discrete values were taken since the spacing needs to be a value such that the number of pipes in the given area is a whole number.

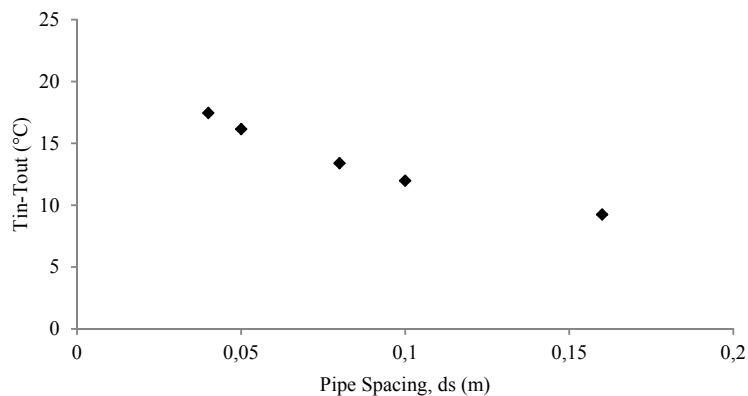


Fig. 5. The performance of a CSC with varying pipe spacing ( $d_s$ )

The values in the literature ranged from 0.04 m [16] to 0.165m [12]; for this range the change in temperature difference is 8.2°C. The spacing of the pipes is most likely to be limited by the bends in the pipe which will also be dictated by pipe material.

### 3.6. Mass flow rate

The mass flow rate is a parameter that can be easily adjusted upon construction of the CSC, however is worth considering. Increasing the mass flow rate,  $\dot{m}$ , results in a greater amount of energy available at the outlet. However, due to the high thermal capacity of the concrete absorber the rate of heat transfer from the concrete domain to the pipes is slower, thus a high temperature difference is not achievable at high flow rates, as displayed in Fig. 6.

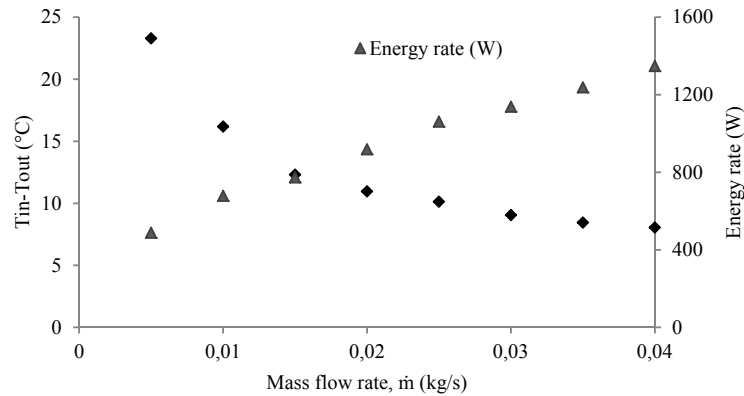


Fig. 6. The performance of a CSC with varying mass flow rate ( $\dot{m}$ )

Fig. 6 displays the mass flow rate with temperature difference, as is the case in the previous Figures. Additionally, the energy rate is displayed to highlight the effect of changing the mass flow rate on the energy output. While the energy output increases with increasing mass flow rate the temperature difference reduces significantly. In this particular application it is important to maximize the temperature difference, thus a slower flow rate is used. An increase in the temperature difference of 5.2°C can be achieved by reducing the flow rate from 0.02 kg/s (average value from the literature) to 0.01 kg/s (minimum value found in literature [5])

## 4. Analysis and discussion

The effect of changing the individual parameters has been presented in the previous section. Using the benchmark parameter values alone results in a temperature difference of 16.17°C while using the best performing values taken from the results gives a temperature difference of 23.75°C; in contrast combining the minimum values results in temperature difference of only 0.5°C. These results show that there is significant room for improvement in terms of the CSC's performance from the benchmark parameters. However, the improvements made to the CSC should not be such that the cost is significantly increased, which is one of the primary benefits of using CSCs in place of standard flat plate or evacuated tube collectors. Fig. 7 displays the performance for each of the six variables assessed using the maximum and minimum values obtained in the literature, thus highlighting the parameters with the greatest influence on the CSC's performance.



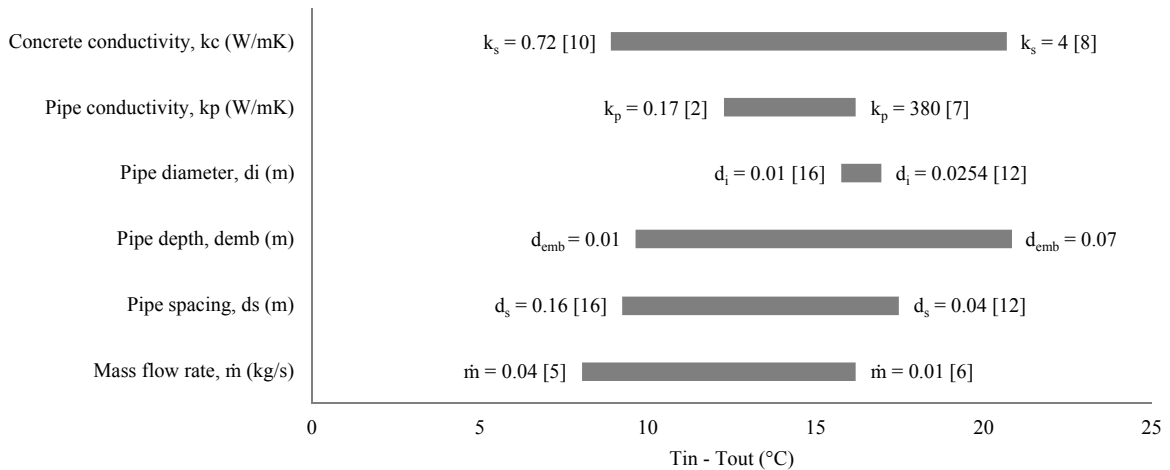


Fig. 7. The performance of CSCs with minimum and maximum parameter values taken from the literature

The concrete conductivity,  $k_c$ , displays the greatest variance in temperature difference (11.7°C) between values obtained in the literature. The embedment depth,  $d_{emb}$ , varied greatly throughout the literature and is influenced by the thickness of the CSC. The maximum and minimum values mark upper and lower embedment depth for the 0.08m thick collector. These values are not strictly taken from the literature since they are dependent on the collector's thickness. Fig. 7 highlights the embedment depth as the second most influential parameter based on this analysis displaying a rise in temperature of 11.1°C between minimum and maximum. Another influential parameter is the pipe spacing,  $d_s$ , displaying an increase of 8.2°C between maximum and minimum values. The minimum pipe spacing is also influenced by the rigidity of the pipe material used. The pipe material used has a lower influence on the temperature difference (3.9°C), particularly considering the broad range of values found in the literature (0.17 - 380 W/mK). Of the physical parameters assessed the pipe diameter displayed the lowest variance in temperature difference (<1.2°C). The mass flow rate is a parameter which can be varied upon construction but has highlighted an increase in temperature difference, but not the energy output, with reducing mass flow rate. A range of 8.14°C has been observed in this study between minimum and maximum values obtained from the literature.

## 5. Conclusion

A review of the CSC literature showed a significant variance in the material properties and geometric dimensions of CSCs. The lack of consistency throughout the literature, both in terms of CSC type and performance criteria to which the CSCs can be compared, has highlighted the requirement for a benchmark CSC for which these uncommon collectors can be compared against. Thus allowing for performance optimization. This numerical based study defined a benchmark CSC based on a combination of the available literature and practical limits, allowing for the comparison of individual parameters.

Six physical parameters (concrete conductivity,  $k_c$ , pipe conductivity,  $k_p$ , pipe diameter,  $d_i$ , pipe embedment depth,  $d_{emb}$ , pipe spacing,  $d_s$  and mass flow rate,  $\dot{m}$ ) have been highlighted as potentially influential variables on the heat transfer from the surface of the CSC to the fluid outlet.

- Of the six variables the concrete conductivity,  $k_c$ , has shown the greatest influence. This parameter is particularly interesting considering the majority of research focuses on reducing the conductivity of concrete facades; in the case of CSCs an increase in conductivity is desirable. A minimum of 2 W/mK should be achieved in order to provide a useful temperature difference. Future research aims at achieving higher conductivities while minimizing the cost of doing so.

- The pipe embedment depth displayed the second greatest influence on the temperature difference. As expected locating the pipes closer to the surface results in a greater temperature difference; however, the type of concrete used and the exposure conditions limits this. Embedding the concrete to a certain depth is important from an aesthetic point of view and the distance from the surface is limited by the exposure conditions of the concrete face in order to preserve the durability of the collector.
- Reducing the distance between individual pipes also displayed a positive influence on the performance. More pipes means a greater heat transfer area between the concrete domain and heat transfer fluid (in this case water), however, the minimum distance is limited by the type of piping used.
- The material of the pipe displayed a smaller influence over a broad range of values but did highlight a 3.9°C decrease in temperature difference when PVC pipes are used in place of metal pipes. The cost of plastic pipes would reduce the overall cost of the collector, meaning money could be spent in more influential areas such as the concrete conductivity or the pipe spacing.
- The pipe diameter showed very little influence on the performance (<1.2°C) for the range in values found in the literature and additionally is limited by standard piping dimensions.
- The mass flow rate is a more complex parameter since increasing the mass flow rate increases the energy output, however also reduced the temperature difference. For this case a high temperature difference is desirable, therefore a low mass flow rate would be more suited. Furthermore, a lower mass flow rate would also require less pumping power.

The next step in the optimization of the CSC will be to validate the model against experimental results. A hot plate will be used to apply the 40°C temperature boundary. Additionally, transient boundary conditions will be applied to the model to simulate daily solar irradiance for different climates at different times in the year in order to identify the storage capabilities of the CSC. Finally, the optimized collector can be tested under real operating conditions. CSCs offer a suitable option for façade integration of concrete clad buildings. Given their lower thermal output compared with other standard collector it is paramount that their performance is maximized while keeping the capital cost low.

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